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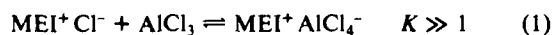
## Ionic Structure and Interactions in 1-Methyl-3-ethylimidazolium Chloride- $\text{AlCl}_3$ Molten Salts

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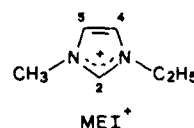
**Abstract:** Room temperature chloroaluminate molten salts formed by mixing 1-methyl-3-ethylimidazolium chloride ( $\text{MEICl}$ ) with  $\text{AlCl}_3$  are of interest as electrolytes and nonaqueous reaction media. Results of NMR studies of  $\text{MEI}^+$  in melts of various composition (determined by the mole fraction,  $N$ , of  $\text{AlCl}_3$  used in forming a melt) were originally explained by a stack model of the ionic structure. In this model, the anions are located between stacked "parallel"  $\text{MEI}^+$  ring planes. An alternative model has been suggested in which  $\text{Cl}^-$  forms ion pairs with  $\text{MEI}^+$  by a H-bonding interaction through the H on the C-2 in the ring. Our IR studies, particularly on deuteriated  $\text{MEI}^+$ , now show that  $\text{Cl}^-$  interacts with the hydrogens at the C-2, C-4, and C-5 members of the  $\text{MEI}^+$  ring.

One of the most widely studied room temperature melt systems is the 1-methyl-3-ethylimidazolium chloride- $\text{AlCl}_3$  ( $\text{MEICl}-\text{AlCl}_3$ ) melt which is liquid at room temperature for compositions between 33 and 67 mol %  $\text{AlCl}_3$ .<sup>1,2</sup> This melt exhibits acid-base chemistry which is dictated by the following reactions:



When the mole fraction of  $\text{AlCl}_3$  ( $N$ ) used in preparing the melt is less than 0.5, it contains  $\text{Cl}^-$ , which acts as a Lewis base, and is basic. For compositions with  $N > 0.50$ , the melt is considered acidic because it contains  $\text{Al}_2\text{Cl}_7^-$ , which acts as a Lewis acid. At  $N = 0.50$  the melt is neutral, with  $\text{AlCl}_4^-$  the only detectable anion. These melts exhibit several attractive features such as large

electrochemical windows and high conductivities. The structure of  $\text{MEI}^+$  is shown below:



A better understanding of the physical and chemical properties of these melts has been sought through investigation of their ionic interactions. The crystal structure of  $\text{MEICl}$ 's iodide analogue,  $\text{MEII}$ , has been reported, and based upon the C-2 hydrogen-iodide distance and position, an interaction involving hydrogen bonding through the C-2 hydrogen has been suggested.<sup>3</sup> Previous investigations have also used this model to explain composition dependent features in the IR spectra of basic  $\text{MEICl}-\text{AlCl}_3$  melts.<sup>4</sup> In the work reported here we studied both normal and deuteriated

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(4) Tait, S.; Osteryoung, R. A. *Inorg. Chem.* **1984**, *23*, 4352.

$\text{MEI}^+$  in melts of various composition. We also examined the bromide analogues of these melts, the effects of solvent addition, and the replacement of the C-2 hydrogen with methyl. Semi-empirical molecular orbital calculations were used to supplement our experimental observations and explore possible structures through which the ions interact in these melts.

### Experimental Section

**General Procedures.** The purification of  $\text{AlCl}_3$  and the preparation of  $\text{MEICl}$  from 1-methylimidazole and ethyl chloride have been presented earlier.<sup>1</sup> Bromide analogues of these melts were prepared with the same techniques. 1,2-Dimethyl-3-ethylimidazolium chloride ( $\text{MMEICl}$ ) was prepared in the same way with 1,2-dimethylimidazole and ethyl chloride. Benzene- $d_6$  (Aldrich) and dichloromethane- $d_2$  (Aldrich) for solvent studies were used as received. Benzene (Aldrich, HPLC grade) and dichloromethane for the dilution of melts (Baker, HPLC grade) were purified by refluxing over  $\text{P}_2\text{O}_5$  for several days followed by fractional distillation.

The IR spectra were recorded on an IBM Model 32 FTIR spectrometer. The solutions were run between NaCl plates (Wilmat,  $41 \times 32 \times 6$  mm) as thin films or with lead spacers of appropriate thickness. All loading of IR cells was done in a He-filled drybox with less than 10 ppm  $\text{H}_2\text{O}$  air.

**Preparation of  $\text{MEICl-2-}d_1$ .** A solution of 4 g of  $\text{MEICl}$  in 10 mL of  $\text{D}_2\text{O}$  was allowed to stand for 3 days. The water was evaporated under reduced pressure and then, to remove the remaining water, the resulting material was suspended in benzene and distilled until the distillate was clear. IR analysis of the material dried by this procedure showed that there was still a small amount of water present so the material was suspended in about 30 mL of benzene and treated with about 0.5 mL of thionyl chloride. After the solution was left to stand for 0.5 h, the benzene and thionyl chloride were removed under reduced pressure and the resulting semisolid was stored under vacuum overnight. The material prepared in this manner showed no water when analyzed by IR, and its  $^1\text{H}$  NMR spectrum showed only a small peak, about 4% hydrogen at C-2.

**Preparation of  $\text{MEICl-2,4,5-}d_3$ .** A solution of 4.0 g of dry  $\text{MEICl}$  in 45 mL of  $\text{D}_2\text{O}$  and about 200 mg of dry  $\text{K}_2\text{CO}_3$  was heated to about  $100^\circ\text{C}$  for 15 h and the water removed under reduced pressure on a rotary evaporator. The residue was mixed with benzene and distilled to remove excess water, and then 0.5 mL of  $\text{SOCl}_2$  was added to complete the removal of water. The benzene and thionyl chloride were then removed under reduced pressure and the resulting material dried under vacuum by heating to about  $80^\circ\text{C}$ . This material, when analyzed by  $^{13}\text{C}$  NMR, showed about 5% hydrogen at C-2, and no detectable hydrogen at C-4 or C-5.

**Theoretical Considerations.** Theoretical calculations were carried out with the standard AM1<sup>5</sup> and MNDO<sup>6</sup> models as incorporated in the MOPAC program.<sup>7</sup> Geometries were fully optimized with the DFP method<sup>8</sup> and refined by minimizing the scalar gradient of the energy.<sup>9</sup> True minima were characterized by the absence of negative force constants,<sup>9</sup> and vibrational frequencies were calculated for the normal modes.<sup>10</sup>

AM1 was preferred over MNDO due to the problem of excessive long-range repulsions associated with MNDO and the capability of AM1 to predict hydrogen bonding.<sup>5,11</sup> Unfortunately, determination of AM1 parameters for aluminum is not yet completed. Consequently, the MNDO parameters for aluminum were used in AM1 calculations involving the interaction of  $\text{AlCl}_4^-$  ions with  $\text{MEI}^+$ . This less than ideal procedure was justified in this study since the AM1 results for  $\text{AlCl}_4^-$  (using MNDO parameters for Al only) were similar to straight MNDO results.<sup>12</sup> Also the interaction between  $\text{AlCl}_4^-$  and  $\text{MEI}^+$  is primarily electrostatic in nature or involves only the chlorine atoms. There is no direct interaction of aluminum with the  $\text{MEI}^+$  and essentially no change in bonding to aluminum is involved.

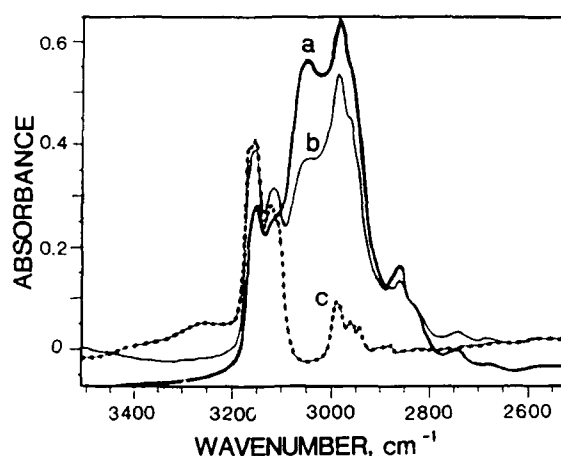


Figure 1. IR spectra of CH bands of  $\text{MEI}^+$  in  $\text{MEICl-AlCl}_3$  melt at (a)  $N = 0.33$ , (b)  $N = 0.40$ , and (c)  $N = 0.50$ .

### Results and Discussion

The vibrational spectra of the  $\text{MEICl-AlCl}_3$  ambient temperature melts carried out by Tait and Osteryoung<sup>4</sup> were re-examined. They found that the IR spectra of  $\text{MEI}^+$  in acidic and neutral melts were the same, but that in basic melts, which contain  $\text{Cl}^-$ , some bands changed in intensity and a new broad band appeared in the C-H stretching region. They suggested that  $\text{Cl}^-$  might form a hydrogen bond with the C-2 hydrogen of the  $\text{MEI}^+$  cation to explain this observation.

In  $^1\text{H}$  NMR studies,<sup>13</sup> the proton chemical shifts of the C-2 hydrogen show the largest changes as the composition of the melt is changed. This provides supportive evidence for the hydrogen-bonded complex, but it was noted that the chemical shifts of the C-4 and C-5 hydrogens are also functions of composition in basic melts.

**IR Spectra.** The IR spectra of  $N = 0.33, 0.40$ , and  $0.50$  melts of  $\text{MEICl-AlCl}_3$  are shown in Figure 1. The most obvious feature in this set of spectra is the appearance of the broad band at  $3049\text{ cm}^{-1}$  as the melts become more basic, i.e., as more  $\text{Cl}^-$  is present. We call this band the  $\text{Cl}^-$  interaction band. The bands between  $3100$  and  $3200\text{ cm}^{-1}$  appear to decrease in intensity as the fraction of  $\text{Cl}^-$  is increased. However, because we used a thin film whose thickness was not precisely controlled, this is only a qualitative observation based on comparison with other spectral features. For example, the bands at  $2900\text{--}3000\text{ cm}^{-1}$  in basic and neutral melts would not be expected to differ significantly in intensity after the  $\text{Cl}^-$  interaction band is subtracted out. There is a further drawback to the lack of control over the sample thickness. We do not obtain the clear isosbestic point that Tait and Osteryoung<sup>4</sup> identified at  $3103\text{ cm}^{-1}$  and attributed to the presence of at least two species whose concentrations vary with acidity.

Our theoretical predictions of the IR spectra of an isolated gas-phase  $\text{MEI}^+$  ion (see next section) identify the band at  $3118\text{ cm}^{-1}$  as the C-2 hydrogen stretch frequency and the bands at  $3150\text{--}3200\text{ cm}^{-1}$  as the C-4 and C-5 hydrogen stretches. The bands at  $2900\text{--}3000\text{ cm}^{-1}$  are due to C-H stretches in the methyl and ethyl groups.

The  $\text{Cl}^-$  interaction band was compared with the  $\text{Br}^-$  interaction band in IR spectra of  $N = 0.33$  melts of  $\text{MEIBr-AlBr}_3$  and  $\text{MEICl-AlCl}_3$ . The important result of this comparison is that the spectral features are virtually the same except that the frequency of the  $\text{Br}^-$  interaction band is at  $3063\text{ cm}^{-1}$ . Thus the interaction with  $\text{Br}^-$  appears to be weaker than that with  $\text{Cl}^-$ , with its larger charge/volume ratio. While these spectra confirm that the band is due to halide interaction with  $\text{MEI}^+$ , it does not tell us which C-H stretch (or stretches) we are observing in the interaction band.

One way of determining if the  $\text{Cl}^-$  interaction band is the stretching frequency of the C-2 hydrogen with a  $\text{Cl}^-$  interacting

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(7) Stewart, J. J. P. *Quantum Chem. Prog. Exchange Bull.* **1986**, *6*, 91; QCPE Program 455, Version 3.1.

(8) (a) Fletcher, R.; Powell, M. J. D. *Comput. J.* **1963**, *6*, 163. (b) Davidson, W. C. *Ibid.* **1968**, *10*, 406.

(9) (a) Komornicki, A.; McIver, J. W. *J. Chem. Phys. Lett.* **1971**, *10*, 303.

(b) Komornicki, A.; McIver, J. W. *J. Am. Chem. Soc.* **1971**, *93*, 2625.

(10) Dewar, M. J. S.; Ford, G. P.; McKee, M. L.; Rzepa, H. S.; Thi, W.; Yamaguchi, Y. *J. Mol. Struct.* **1978**, *43*, 135.

(11) Dewar, M. J. S.; Dieter, K. M. *J. Am. Chem. Soc.* **1986**, *108*, 8075.

(12) The MNDO heat of formation for  $\text{AlCl}_4^-$  is  $-273.4\text{ kcal/mol}$ , the Al-Cl bond length is  $2.15\text{ \AA}$ , and the atomic charges on Al and Cl are  $0.90$  and  $-0.47$ , respectively. The corresponding AM1 results are  $-263.2\text{ kcal/mol}$ ,  $2.07\text{ \AA}$ ,  $0.64$ , and  $-0.41$ .

(13) Fannin, A. A., Jr.; King, L. A.; Levisky, J. A.; Wilkes, J. S. *J. Phys. Chem.* **1984**, *88*, 2609.

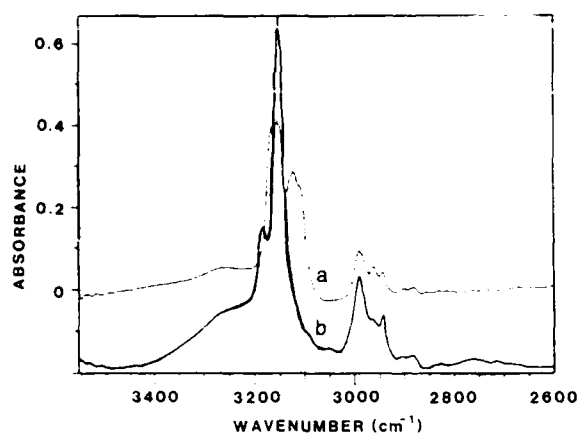


Figure 2. IR spectra of CH bands of (a) MEI<sup>+</sup> and (b) MMEI<sup>+</sup> both in  $N = 0.50$  melt.

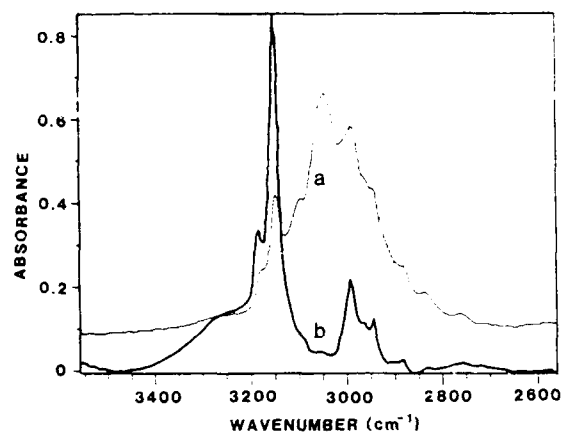


Figure 3. IR spectra of CH bands of MMEI<sup>+</sup> in MMEI-Cl-AlCl<sub>3</sub> melt at (a)  $N = 0.33$ ,  $T = 140$  °C and (b)  $N = 0.50$ ,  $T = 100$  °C.

with it through a hydrogen bond is to replace the C-2 hydrogen with a methyl group to form 1,2-dimethyl-3-ethylimidazolium chloride (MMEI-Cl). In Figure 2 we show the spectra of MEI<sup>+</sup> and MMEI<sup>+</sup> in AlCl<sub>3</sub> melts with  $N = 0.50$ . The absence of the band at 3118 cm<sup>-1</sup> in the MMEI<sup>+</sup> spectrum confirms our assignment of this band as the C-2 hydrogen stretch in MEI<sup>+</sup>. In Figure 3 the  $N = 0.33$  and 0.50 melts of MMEI<sup>+</sup> are compared. The appearance in the MMEI<sup>+</sup> spectrum of the Cl<sup>-</sup> interaction band at 3049 cm<sup>-1</sup> is the first strong evidence that this band in the MEI<sup>+</sup> spectrum cannot be attributed solely to a C-2 hydrogen stretching frequency shifted by hydrogen bonding with Cl<sup>-</sup>.

Further evidence that the Cl<sup>-</sup> interaction band is not a hydrogen-bonded C-2 hydrogen-stretching frequency is shown in Figure 4. Here the IR spectrum of a neat MEI-Cl-AlCl<sub>3</sub> melt with  $N = 0.33$  is compared with those of solutions of this same melt with dichloromethane-*d*<sub>2</sub> and benzene-*d*<sub>6</sub> in the concentrations shown. The effect of these solvents is to reduce the intensity of the interaction band. This effect, especially with benzene, would not be expected if the Cl<sup>-</sup> were forming a hydrogen bond with the MEI<sup>+</sup>, unless the bond was quite weak.

To determine which C-H stretching frequencies shift to form the Cl<sup>-</sup> interaction band, we deuteriated first the C-2 and then the C-2, C-4, and C-5 positions of MEI-Cl. On the basis of NMR analysis and the quantities of D<sub>2</sub>O and MEI<sup>+</sup> used in the H-D exchange reactions, we conclude that the MEI-Cl-2-*d* and the MEI-Cl-2,4,5-*d*<sub>3</sub> used were deuteriated to the extent of 95–97% and 90–95%, respectively. The IR spectra of the  $N = 0.33$  and 0.50 deuteriated melts are compared with those of the undeuteriated melts in Figure 5. In each spectrum we observe only the normal C-H or C-D stretches in the  $N = 0.50$  melts and the appearance of the Cl<sup>-</sup> interaction band in the  $N = 0.33$  melts. With only the C-2 position deuteriated, interaction bands appear in both the C-H and C-D stretching regions. Clearly the C-2 deuterium stretch at 2350 cm<sup>-1</sup> is shifted to about 2280 cm<sup>-1</sup> by

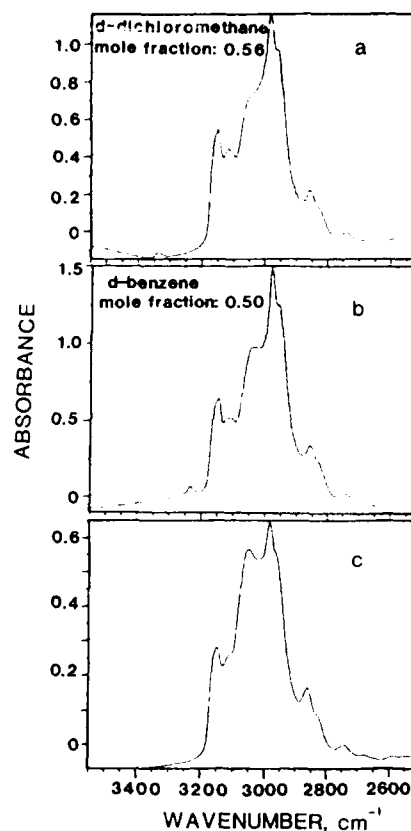


Figure 4. IR spectra of CH bands of MEI<sup>+</sup> in  $N = 0.33$  melt and nonaqueous solutions of this melt: (a) dichloromethane-*d*<sub>2</sub>, (b) benzene-*d*<sub>6</sub>, (c) neat melt.

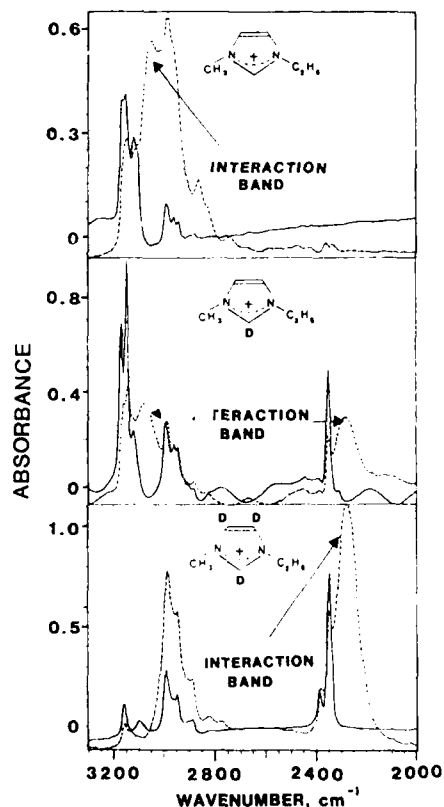


Figure 5. IR spectra of undeuteriated MEI<sup>+</sup> in  $N = 0.50$  melts (no interaction bands) and  $N = 0.33$  melts (with interaction bands indicated).

the presence of Cl<sup>-</sup>. However, the C-4 and C-5 hydrogen stretches apparently are also shifted to form the interaction band at about 3060 cm<sup>-1</sup>. When C-4 and C-5 are also deuteriated, the interaction

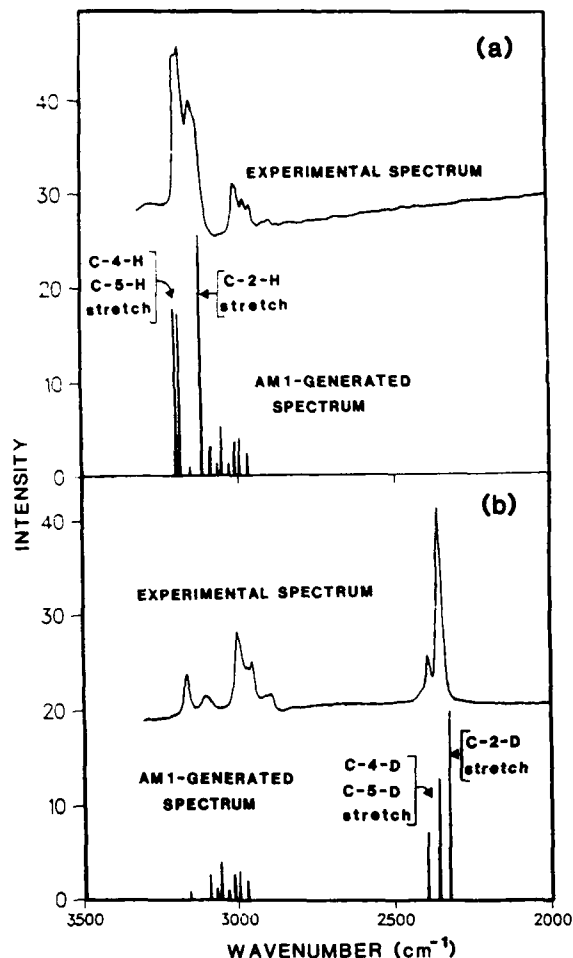


Figure 6. IR spectrum of  $N = 0.50$   $\text{MEI}^+\text{-AlCl}_3$  melt and AM1-generated spectrum of isolated  $\text{MEI}^+$ : (a) undeuterated, (b)  $\text{MEI}^+\text{-2,4,5-}d_3$ .

band appears only in the C-D stretching region along with the normal C-2, C-4, and C-5 deuterium stretching frequencies. Note that this sequence of spectra also confirms our assignments of the C-4 and C-5 hydrogen-stretching frequencies. Figure 5 thus strongly supports a model in which  $\text{Cl}^-$  can interact nearly equally with all three ring hydrogens.

**Theoretical Calculations.** While AM1 and MNDO were parametrized with gas-phase data, MNDO results were previously shown to be consistent with the experimental IR spectra of  $\text{Al}_2\text{Cl}_7^-$  in molten  $\text{KAl}_2\text{Cl}_7$ .<sup>14</sup> For the isolated  $\text{MEI}^+$  ion, AM1 results shown in Figure 6a again provide a reasonable model of the 2900–3300- $\text{cm}^{-1}$  region of the experimental IR spectrum results for the  $N = 0.50$  melt, in which there is no  $\text{Cl}^-$  to interact with the  $\text{MEI}^+$ . While the intensity of the C-2 hydrogen stretch is overestimated, its position and the positions and relative intensities of the alkenyl and alkyl C-H stretches are well represented. Thus the AM1 results confirm our assignment of frequencies based on experimental results. In Figure 6b the experimental and calculated spectra of  $\text{MEI}^+\text{-2,4,5-}d_3$  are compared. Again, the overall features agree very well. Even more remarkable is that the changes in the relative frequencies and intensities of the C-4, C-5, and C-2 hydrogen stretches observed upon substitution with deuterium are nicely predicted by the AM1 results.

We did attempt to find a stable configuration in which  $\text{Cl}^-$  was hydrogen bonded to the C-2 hydrogen of  $\text{MEI}^+$ . A  $\text{Cl}^-$  was positioned to hydrogen bond to the C-2 hydrogen and the geometry was optimized. In the predicted stable configuration, the C-2-hydrogen bond was almost totally broken, with the C-2-hydrogen and H-Cl distances optimizing at 1.56 and 1.40 Å, respectively. The C-2-hydrogen stretch was strongly coupled with the H-Cl

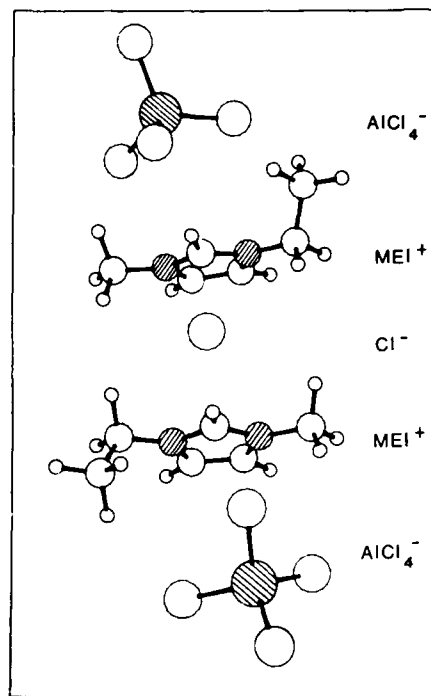


Figure 7. Fully optimized configuration of the  $\text{AlCl}_4^-$ - $\text{MEI}^+$ - $\text{Cl}^-$ - $\text{MEI}^+$ - $\text{AlCl}_4^-$  system calculated with AM1.

stretch, two vibrations appearing at 1565 and 711  $\text{cm}^{-1}$ . These results are no doubt exaggerated due to AM1 underestimating the stability of the chloride anion ( $\Delta H_f = -37.7$  kcal/mol (calcd),  $-55.9$  kcal/mol (exptl)<sup>15</sup>). Further, no other counterions were present in the system, leaving the  $\text{Cl}^-$  attack on the C-2 hydrogen as its only avenue for stabilization. Interestingly, even when an  $\text{AlCl}_4^-$  was substituted for the  $\text{Cl}^-$ , the interaction between one chlorine atom and the C-2 hydrogen was strong enough to shift the C-2-hydrogen stretch from 3118  $\text{cm}^{-1}$  in the isolated  $\text{MEI}^+$  to 2492  $\text{cm}^{-1}$  in the complex. This shift is too large to be explained fully by the change in reduced mass. While this result is again exaggerated due to the treatment of the complex as a totally isolated ion pair, the gas-phase calculation suggests that a hydrogen bond between a  $\text{Cl}^-$  and the C-2 hydrogen would cause a larger red shift in the C-2-hydrogen stretch than to the 3049- $\text{cm}^{-1}$  frequency observed.

According to AM1 calculations, the  $p\pi$  orbital of C-2 contributes 50% to the lowest unoccupied molecular orbital (LUMO) of the isolated  $\text{MEI}^+$ . When a  $\text{Cl}^-$  was centered above the ring and the geometry optimized, the  $\text{Cl}^-$  shifted to form a covalent bond with the C-2. The heat of formation for this covalent species was 4.6 kcal/mol less than that for the "hydrogen-bonded" complex, and the frequency of the C-2-hydrogen stretch was predicted to be 2951  $\text{cm}^{-1}$ . When a second  $\text{MEI}^+$  was positioned parallel to the first  $\text{MEI}^+$ , with the  $\text{Cl}^-$  centered between the two rings, and the geometry fully optimized, a minimum was located with the  $\text{Cl}^-$  located slightly in front of the two C-2's and nearly equidistant from both (C-2-H = 2.48 Å, C-2'-H = 2.42 Å). This complex was predicted to be 8.4 kcal/mol more stable than the covalent  $\text{MEI}^+$  species plus an isolated  $\text{MEI}^+$ . The C-2-hydrogen stretch for the complex was red shifted relative to that of the isolated  $\text{MEI}^+$ , its frequency being 3107  $\text{cm}^{-1}$  vs 3118  $\text{cm}^{-1}$  for the isolated  $\text{MEI}^+$ .

A slightly more extensive stack model was constructed by placing a  $\text{Cl}^-$  between two parallel  $\text{MEI}^+$  ions and placing two  $\text{AlCl}_4^-$ 's on the outer sides of the  $\text{MEI}^+$  ions. The fully optimized geometry calculated for this configuration is shown in Figure 7. Again, in the most stable geometry, the  $\text{Cl}^-$  is nearly equidistant

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between the two nearly parallel  $\text{MEI}^+$  ions. A similar structure with the central  $\text{Cl}^-$  replaced by an  $\text{AlCl}_4^-$  was also optimized so that frequencies of the C-H stretches could be compared. The frequency of the C-2-hydrogen stretch for this model was  $3111\text{ cm}^{-1}$  compared to the  $3107\text{ cm}^{-1}$  for the Figure 7 system with  $\text{Cl}^-$  thus reproducing the direction (but not the magnitude) of the shift observed to form the  $\text{Cl}^-$  interaction band. However, the C-4- and C-5-hydrogen stretches shifted from  $3225$  and  $3238\text{ cm}^{-1}$  with no  $\text{Cl}^-$  present to  $3239$  and  $3251\text{ cm}^{-1}$  in the Figure 7 structure. Thus the calculated shift is in the opposite direction from that observed and leads us to conclude that the AM1 method is not capable of reproducing the experimentally observed  $\text{Cl}^-$  interaction band frequencies using this model. Nonetheless, two important results were obtained from the AM1 calculations. First is the confirmation of the assignments of the C-2-, C-4-, and C-5-hydrogen stretching frequencies. Second is the identification of  $\text{Cl}^-$  centered between two adjacent  $\text{MEI}^+$ 's (Figure 7) as a stable configuration for this system.

### Conclusion

In basic melts of  $\text{MEICl}$  and  $\text{AlCl}_3$ , our IR spectral analysis showed that  $\text{Cl}^-$  interacts with  $\text{MEI}^+$  to cause similar shifts in the frequencies of the C-2-, C-4-, and C-5-hydrogen stretches. Thus the description of the interaction of  $\text{MEI}^+$  with  $\text{Cl}^-$  cannot be restricted to ion pair formation solely by hydrogen bonding of  $\text{Cl}^-$  through the C-2 hydrogen. Our experimental results are consistent with a stack model for the interaction of  $\text{MEI}^+$  with the anions in the melt, although the inability to theoretically predict the experimental shifts in ring C-H frequencies leaves the exact nature of the interactions an open question.

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